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Analysis of Zoned Residential Ventilation Systems

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ABSTRACT

Trends in home heating and cooling in the US are resulting in less mixing of air within dwellings, either due to not using central forced air systems, or to reduced loads and runtimes in high performance homes. This study examined the use of zoned ventilation systems using a coupled CONTAM/EnergyPlus model of new California dwellings, including a 1-story single-family dwelling and a single apartment unit. Zoned and unzoned ventilation systems were simulated for exhaust, supply and balanced fan types. Smart controls were designed to reduce ventilation energy use and provide equivalent occupant pollutant exposures, using metrics that allow the efficacy of ventilation to be calculated on a zonal basis. The key metric was the personal exposures of the dwelling occupants to a number of contaminants of concern, including moisture, formaldehyde, CO_2, particles and a generic contaminant., Emission rates were based on previous field studies and research literature, and they include a mixture of episodic and background emissions that were scheduled to align with zone occupancy patterns and activities (e.g., cooking, bathing, sleeping). These personal exposures were compared for smart controlled and baseline reference cases to ensure equivalence, as well as between zoned and unzoned fan types. Results showed that while zonal ventilation has the capability to save energy beyond that offered by single-zone approaches, care is required in the design and evaluation of zonal controls because all control types led to increased personal exposures for at least one of the contaminants. Substantial differences were identified between fan types, in terms of their ability to deliver outside airflow to occupied zones, the resulting personal pollutant exposures, and in energy performance.

INTRODUCTION

This study uses energy and airflow modeling to explore minimizing the energy penalty associated with conditioning ventilation air in residences while ensuring acceptable indoor air quality. The focus is on ventilation systems that can ventilate part of a home, while not ventilating others, i.e., zonal ventilation. To ensure that indoor air quality is not compromised, the concept of *personal relative exposure* is used in this study. Relative exposure is a unitless number found by determining the ratio of personal exposure for a given ventilation approach or system to the exposure from a reference case: a continuously emitted, indoor generic pollutant and a continuously operated ventilation fan sized to ASHRAE 62.2 (ASHRAE 2016). For control purposes, this study also uses *relative dose* that is the running 24-hour average of relative exposure. A relative exposure less than or equal to one ensures that the exposure from a smart ventilation system is equivalent to or better than a non-controlled system. The relative exposure approach is particularly useful for zonal ventilation control strategies that are occupancy-based because it can be adapted such that it is evaluated only during times of occupancy of a particular zone.

Zonal approaches to ventilation fall under the definition of "smart ventilation" as defined by the Air Infiltration and Ventilation Center (AIVC 2018). The smart ventilation strategies in this study modulate ventilation rates throughout the course of a day or year and for different rooms (or zones) in the home. These strategies may respond to outdoor air temperature, zone occupancy, predicted exposures, measured indoor contaminants, and the operation of auxiliary ventilation devices such as bathroom fans. A thorough review of available smart ventilation strategies that have been previously studied can be found in Guyot et al. 2018. The zonal control approaches evaluated in this work build on the single zone ventilation control strategies developed in Less et al. 2019 and Clark et al. 2019. If zones are reasonably well isolated from one another, then a ventilation system could be controlled to only ventilate occupied zones and potentially saving on ventilation energy requirements. All data used in this paper are available in Dryad (Less et al. (2021)).

MODELING APPROACH

The various strategies were assessed analytically using computer simulations combining the CONTAM air flow and pollutant transport and EnergyPlus building loads models. All of the analyses use detailed annual simulations of reference buildings with thermal and airflow characteristics of homes built to the 2019 Residential Building Energy code in California (California Energy Commission 2019). This energy code has specific prototype buildings that we used in this study: A 1-story single-family dwelling (195 m^2) and a single apartment unit from the multi-family prototype (81 m^2). The single family dwelling had a range of envelope leakage of 0.6, 2 and 3 ACH_{50}. The apartment dwellings were simulated only at one envelope leakage level (3 ACH_{50}) and all apartment surfaces, aside from one exterior wall, were treated as perfectly sealed from adjacent units in the building and without heat transfer. The weather-variability of natural infiltration and energy requirements to condition ventilation air was included by using four California climate regions (1, 3, 10 and 16), ranging from temperate coastal (CZs 1 and 3), through hot inland (CZ 10) to the colder and dry mountain regions (CZ16). Two different heating and cooling approaches were analyzed: central forced air heat pump with a MERV13 particle filter that tends to mix air between zones, and distributed heat pump systems with no filtration and much less distribution between zones.

Each dwelling was split into four zones (plus an unoccupied attic for the single-family homes): the kitchen, bathrooms, bedrooms and "other" living spaces. The apartment bedrooms were further divided into adult and child bedroom zones. This division allows us to account for the major difference in locations for pollutant emissions (moisture mostly in wet rooms and particles from cooking in the kitchen), as well as occupancy patterns (relatively small amounts of time in kitchens and bathrooms and several hours of continuous occupancy for bedrooms). Interior doors were only closed for bedrooms during sleeping hours.

Three whole dwelling, non-zoned ventilation systems were simulated for comparison to the zoned systems:

1. Central exhaust located in the other living spaces zone
2. Central supply located in the other living spaces zone, with MERV13 filtration for the supply air. All supply fan flows were assumed to also have a 3-to-1 recirculation flow for tempering. This increased the supply fan energy use by a factor of 4 relative to similar size exhaust fans.
3. Balanced system, with exhaust flows from Kitchen and Bathroom zones, and supply flows (with MERV 13 filtration) to the other living spaces and Bedroom zones

The zoned ventilation systems were:

1. Exhaust fans located in each zone of the dwelling, controlled independently.
2. Supply fans located in each zone of the dwelling, controlled independently.
3. Balanced supply/exhaust systems located in each zone of the dwelling. Note, this differs from current ducted systems, which are balanced for the home, but not for each zone in the home. The system studied here is balanced for each zone.
4. Central exhaust with controlled inlets in each zone.

Whole house target and mechanical fan airflows are calculated using the ASHRAE 62.2-2016 ventilation standard. Target flows for each zone were determined by dividing the whole dwelling flow amongst the zones proportional to their floor area fractions. More details of the specific air flows broken down by each zone are given in Walker et al. (2021). All ventilation fans assumed a fixed watts per unit flow rate of 436.1 watts per m^3/s. For supply ventilation systems the tempering quadrupled fan energy for simple supply systems and quintupled fan energy for balanced systems.

While the simulation tools use a mass balance to fully account for all air flows and pollutant transport between inside and outside and between zones, it is not practical for a ventilation system controller to know all this information. Therefore, the ventilation equivalence calculations use an estimate for the total zone ventilation flow (combination of zone fan and zone infiltration flows) at any given time together with the target for that zone. For the contaminant-sensing simulations this simplification is not required and the ventilation system operates in a zone until all contaminants are below pre-set acceptable levels. A third option was also developed that uses the real-time generic contaminant concentration predicted in each zone by CONTAM, and compares this against the whole dwelling steady-state concentration that would occur at the ASHRAE 62.2 target ventilation rate.

Acceptable limits for indoor contaminant concentrations were determined as follows. For formaldehyde, the OEHHA REL is 9 $\mu g/m^3$ for 8-hour and chronic exposures, and 55 $\mu g/m^3$ for one hour. For particles the WHO Chronic level is 10 $\mu g/m^3$ and 25 $\mu g/m^3$ for 24 hours. The CO_2 limits were 5000 ppm for an individual time step and 1100 ppm for chronic exposure. For moisture a limit of 60% RH was used. Emission rates for moisture, CO_2, formaldehyde and particles were taken from a combination of the literature and derived from measurements in the HENGH field study (Singer et al. 2020). Formaldehyde emissions were uniform throughout the dwelling, but the emission rate varied at each time-step based on indoor temperature, relative humidity, and ventilation rate. Indoor particle emissions included both episodic sources from cooking events (with 50% initial capture and removal by the range hood), as well as background emissions that occurred in zones that were occupied with non-sleeping occupants. CO_2 and water vapor emissions from respiration tracked the occupants, and were emitted in occupied zones based on the number of persons in each zone. Water vapor was also emitted during scheduled bathing events (paired with bathroom exhaust fan operation). More details of the specific emission rates can be found in Walker et al. (2021). For particles, removal by interior deposition, the building envelope for outdoor particles, and media filters was included. Outdoor contaminant levels were assumed to be a constant 400 ppm for CO_2, used weather data for moisture, used US EPA ambient sample data for hourly particle levels in each simulated county, and a fixed 3 ppb for formaldehyde.

SMART CONTROL DESCRIPTIONS

A key aspect of zonal ventilation control is knowing which zones are occupied. All zonal controllers used the zone occupancy as a key control input. A typical 9-hour workday/school day absence from 8-5pm Monday – Friday, with continuous weekend occupancy was assumed. A fixed schedule of occupants moving between rooms at different times of day was imposed, together with scripting their activities within the zones (e.g., person one in the kitchen zone cooking, or person two in the bathrooms taking a shower). More details of occupancy schedules can be found in Less et al. (2020).

In order to isolate the energy used for mechanical ventilation from the other dwelling loads, simulations were performed with infiltration and auxiliary kitchen and bathroom fans, but no whole dwelling ventilation, to provide the non-ventilation energy load that could be subtracted from the simulation results to give the ventilation-related energy. In addition, a baseline simulation was run with a constant flow fan sized to ASHRAE 62.2-2016 to compare to the various smart ventilation approaches. The constant flow baseline cases were run with all fan types, both zonal and non-zonal, including exhaust, supply and balanced fans. The smart ventilation system fans are doubled in their capacity to enable the time shifting of ventilation.

The following smart control strategies were examined:

- **Baseline + Indoor Air Quality (IAQ) Controls.** Intended to improve IAQ while not affecting energy use these controls do not modulate the total air flow, instead they change which zone the air is supplied or exhausted from based on occupancy. Annual ventilation air flows are unchanged.
    - **supplyTracker** – For supply and balanced systems the supply air flows are directed to occupied zones. The total system air flow is directed to each occupied zone in proportion to its floor area. It is possible for a single occupied zone to receive the full dwelling air flow rate.
    - **occupantTracker** – This is the same as the supply tracker, but for exhaust air, such that the exhaust is taken from occupied zones only.
- **Outdoor Temperature Controls.** These controls used measured outdoor temperatures to shift ventilation flows to mild weather periods.
    - **varQ** – For unzoned systems the whole dwelling IAQ fan flow rate is varied according to outdoor dry-bulb temperature, using pre-optimized temperature scaling factors. This leads to increased annual ventilation flow.
    - **varQmzSingleZoneOpt** – For zoned systems, this control has the same airflow as varQ, but zone airflows are directed to occupied zones only. This leads to increased annual ventilation flow.
    - **varQmz** – For zoned systems, this control has the same calculation procedures as varQ, but temperature scaling parameters are optimized for a two-zone dwelling using assumed occupancy patterns. This approach can decrease annual ventilation flow.
- **Zone Occupancy Controls.** Unlike the above **tracker** controls, these controls apportion the whole dwelling flow to each zone and then only vent occupied zones. This reduces annual ventilation airflow for the dwelling. Controls use either estimated relative exposure and dose or actual contaminant predictions.
    - **zoneExposure** – The controller tracks relative exposure and relative dose in each zone, and operates the IAQ fan to maintain both metrics below 1 during occupied periods.

Outside occupied times, relative exposure is controlled to less than 5 to avoid acute exposures.

  - **zoneASHQexposure** – This is the same control strategy as zoneExposure, but instead of using controller estimates of relative exposure and dose, it controls the zone Generic contaminant concentration to be the same as the steady-state zone concentration that would occur at the uncontrolled continuous ventilation rate.
  - **occExposure** – This tracks controller estimated relative exposure in each zone and relative dose for each occupant. Zones are vented if any person in the zone has a relative dose greater than 1, or if the zone relative exposure is greater than 1. Unoccupied zone relative exposure is controlled to less than 5. This controller ensures that a high personal exposure in one zone can be compensated for by increased ventilation and lower exposure upon entering another zone.
  - **occASHQexposure –** This is the same control strategy as occExposure, but instead of using controller estimates of relative exposure and dose, it controls the zone Generic contaminant concentration to be the same as the steady-state zone concentration that would occur at the uncontrolled continuous ventilation rate.
  - **occupantVenter –** All zones get a minimum flow rate when unoccupied. Additional airflow is distributed to occupied zones. There is no tracking of controller estimated exposure, dose or contaminants.
- **Contaminant Controls.** This controller uses actual contaminant concentrations in each zone and ventilates when they exceed health-relevant thresholds. These controls apply to all multipoint zoned systems.
  - **contaminantDwelling** – The whole dwelling is vented if any contaminant exceeds health thresholds in any zone.
  - **contaminantZone** – Each individual zone is vented if any contaminant in the zone exceeds health thresholds.
  - **contaminantZoneOcc -** Each individual zone is vented if it is occupied and any contaminant in the zone exceeds health thresholds.
  - **RHinlets** – Ventilation rate and air inlets are used to increase ventilation when indoor humidity is high. This controller operates at a minimum air flow rate below 30% RH and maximum flow above 70% RH. The flow is adjusted linearly with RH between these limits.

RESULTS FOR MULTI-ZONE AND CONTAMINANT-CONTROLLED VENTILATION

Direct Contaminant Control

Using measured contaminant concentrations led to consistently increased ventilation rates in the dwellings in order to meet the CA OEHHA formaldehyde 24-hour target of 9 μg/m^3. None succeeded in meeting the OEHHA limit despite operating the over-sized fans continuously each hour of the year. The increased ventilation reduced personal exposures to the generic contaminant, formaldehyde and CO_2, but this same outside airflow tended to increase personal particle exposure on average, due to increased exposures to particles of outdoor origin. Beyond a certain point, increasing ventilation to reduce formaldehyde exposures may be counterproductive from a human health perspective. Formaldehyde may be better controlled through reducing its sources, while particles are best controlled through filtration and point source removal in kitchens. Critically, the formaldehyde emission rate model used in this work increases the emission rate as the dwelling ventilation rate increases, which tends to limit the ability of increased ventilation to reduce formaldehyde concentrations. Because the smart ventilation system fans are doubled in their capacity to enable the time shifting of ventilation, their continuous operation to attempt to control formaldehyde led to ventilation energy use that was roughly doubled for these controls. The only way for direct contaminant controls to be otherwise effective would be to use a higher limit for formaldehyde, which might reduce energy use and potentially improve particle exposure.

Ventilation System Type

Fan type has major impacts on the ability to zonally ventilate, as well as on the energy and IAQ performance of baseline and smart control cases. A key issue is that outdoor particles were included in our analysis, and this led to increased personal exposure for zoned systems, because they more effectively deliver outdoor air to the occupants, including outdoor pollution.

Exhaust fans behave the least zonally, and have little impact on personal exposure through being zoned, with the exception of CO_2. Zoned exhaust fans effectively controlled CO_2, because of the ability to selectively vent bedrooms with closed doors during sleep hours. Exhausting directly from this higher concentration zone increased the local ventilation effectiveness. Exhaust fans also have the lowest energy use. For control types that increased annual ventilation flows during mild weather periods (e.g., varQ), the small energy penalty of exhaust fan types ensured good energy performance for these outside temperature based controls. But for controls that reduced annual ventilation flows (e.g., occExposure), the limited fan energy use also lessened the savings potential. The whole dwelling ventilation rates and personal exposures provided by exhaust fans lies between supply and balanced fan types.

Supply fans are highly capable of providing zonally directed outside airflow, and reducing personal pollutant exposures for the generic contaminant, formaldehyde and CO_2. Again, this also means they were more effective at delivering outside particle pollution directly to the occupants, particularly when smart controls used the zone occupancy data to direct all airflow to the occupied spaces. Supply fan cases achieved the lowest mean dwelling infiltration rates, but their high fan energy made them the second highest energy using scenarios, just slightly below balanced fan cases. This high fan energy meant they achieved greater levels of savings when using smart controls that reduced annual outside airflow, but they performed poorly (in most climate zones) for outdoor temperature-based control types that increased annual outside airflow.

Balanced fans were similarly capable of zonally directed outside airflow, and they provided the highest dwelling ventilation rates, lowest exposures, and highest annual HVAC energy use. Balanced fans had the greatest ventilation energy savings for controls that reduced annual outside airflow.

These results imply that effective ventilation zoning requires supply or balanced systems, but that the benefits of zoning are unclear, and the energy savings must overcome their much greater mechanical fan energy use, or lower fan energy technologies must be used or developed. Subsequent simulations have shown more effective zoning for 2-story homes due to concentration gradients between floors. This is discussed in Less et al. (2021).

Dwelling Type

The results showed significant differences in energy impacts between a one story single-family home and an apartment. Smart controls were not able to effectively reduce HVAC energy use in the apartment dwellings, whereas the 1-story cases showed a consistent ability to save energy. This is because the apartments had small heating loads, and their annual HVAC energy use was dominated by cooling demand. The mechanical ventilation of the apartments provided ventilation cooling for most of the year, in most climates, such that reducing ventilation rates did not save energy—instead energy use was increased to offset the loss of “free” ventilation cooling.

Apartment units had overall higher air change rates than the 1-story dwellings (0.41 vs. 0.31 hr^{-1}), due to their smaller volumes and higher occupancy density, and the sizing calculations used for multi-family fans in ASHRAE 62.2-2016, which do not allow reductions in fan airflow for natural infiltration. The higher ventilation rates led to reduced personal exposures in apartments for the generic contaminant and formaldehyde (which were emitted proportional to floor area). Apartments had increased exposure to particles and CO_2 compared to one story dwellings due to higher occupant density, and to similar amounts of cooking contaminant emissions into a much smaller space. While smart controls did not effectively save energy in apartments, they were able to improve IAQ by targeting outside airflows to occupied zones, and these IAQ improvements were generally greater in apartments than in 1-story dwellings for the same control type.

Envelope Leakage

This study focused on mechanically ventilated new dwellings that are not very leaky. Combined with the adjustments for natural infiltration in ASHRAE 62.2, this resulted in very little variability in overall air exchange rate with envelope leakage. Across all 1-story cases, the mean infiltration rates were 0.316, 0.318 and 0.324 hr^{-1} for the 0.6, 2 and 3 ACH_{50} cases, respectively. This resulted in envelope leakage rates having very little impact on pollutant exposures, energy use and energy savings from controllers. The sole exception was for particles, where the leakier dwellings with higher ventilation rates had increased personal exposures from outdoor particles brought indoors. This result implies that, so long as dwellings meet a reasonable 3 ACH_{50} maximum leakage limit, that smart ventilation energy and IAQ performance is relatively independent of envelope leakage.

Climate Zone

Climate zone had substantial impacts on personal pollutant exposures, with CZ16 showing the highest average personal exposures for the generic contaminant, CO_2 and particles, while having by far the lowest formaldehyde exposures. This is because formaldehyde emission rates depend strongly on indoor relative humidity, and the dry CZ16 had much lower emission rates. Climate zone also dominated the variability in annual HVAC energy use, with the coldest location, CZ16, consistently showing both the highest annual consumption, but also the greatest absolute energy savings from smart controls. For example, the best energy savings strategy (varQmz) saved 60% in CZ16 but only 27% in CZ 10.

Number of Control Zones

Many of the zonal smart ventilation controls assessed two zoning configurations—one where each zone in the dwelling was treated independently, and a second where only two zones were considered (bedrooms and non-bedrooms). The results showed that for most contaminants, treating each zone independently worsened personal exposure in 1-story dwellings, and this approach increased ventilation energy savings in these dwellings. Personal exposure likely worsened because as the occupants moved from zone to zone, they continually entered a zone that was previously not well-ventilated. This leaves the controls to always play catchup, and they were not always able to do so. The worsened personal exposure and small increase in energy savings are not justifiable, so we would recommend that zonal smart ventilation systems use fewer, rather than more zones, which should reduce system costs and complexity.

Multizone and Contaminant Control Summary

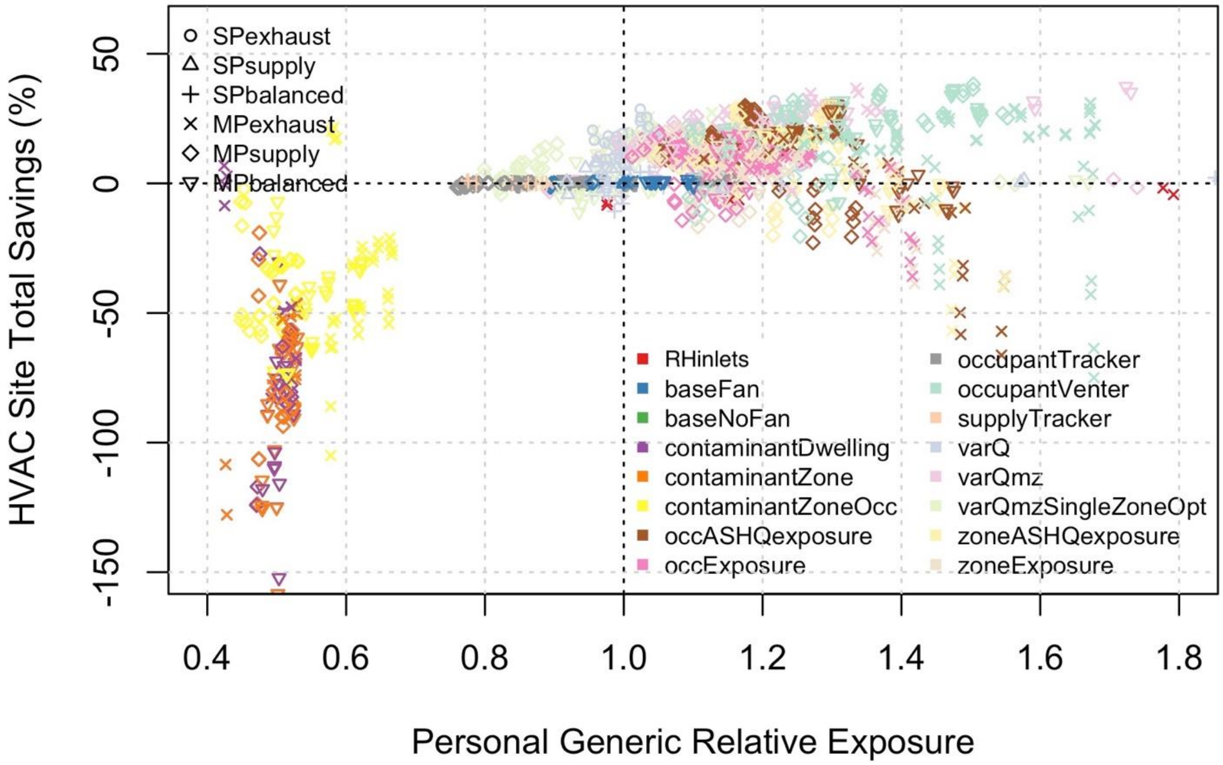

Figure 1 Site Energy Total HVAC Savings (%) and Personal Generic Relative Exposure.

Figure 1 shows the results for total HVAC site energy savings (positive values indicate savings and negative values indicate increased energy use) and changes in personal exposure to the generic contaminant for all the multi-zone controllers (personal exposure > 1 indicates worsened IAQ). This shows that many controls provided whole dwelling HVAC site energy savings of between 0 and 40%. The greatest savings were for the zonal controls that shifted ventilation seasonally (varQmz), and for zone occupancy controls that most aggressively reduced ventilation rates (occVenter and occASHQexposure). These controls all tended to increase personal exposures to the generic contaminant by anywhere from 10 to 70%. To varying degrees, most controllers either use more energy (and reduce some exposures) or have higher relative exposures (and reduce energy use). The varQ non-zonal temperature-based controller saved the most energy while having the smallest negative impact on personal contaminant exposures. For other contaminants the broad patterns across all controllers are the same (i.e., it is difficult to both save energy and reduce exposure), however, the results for each individual controller can vary significantly (for more details see Less et al. (2020).

Figure 2 summarizes the small changes in ventilation rate and personal exposure to individual contaminants between the ventilation system types and whether the system is zoned (multi-point) or not (single point). Note that these results are for constant flow cases with no zoning controls. The personal exposures are reduced with higher ventilation rates associated with the exhaust and balanced fan types. Comparing the zonal and non-zonal results for the generic contaminant (top left pane) illustrate the limited impact of zoning the exhaust fan type (circles), as the blue and black symbols overlap nearly identically. In contrast, the single-point supply fans (triangles) had consistently higher generic exposures than the corresponding zonal supply systems. Particle exposures show the least variability with dwelling ventilation rates, because indoor emission patterns, ambient concentrations and any media filtration are more important.

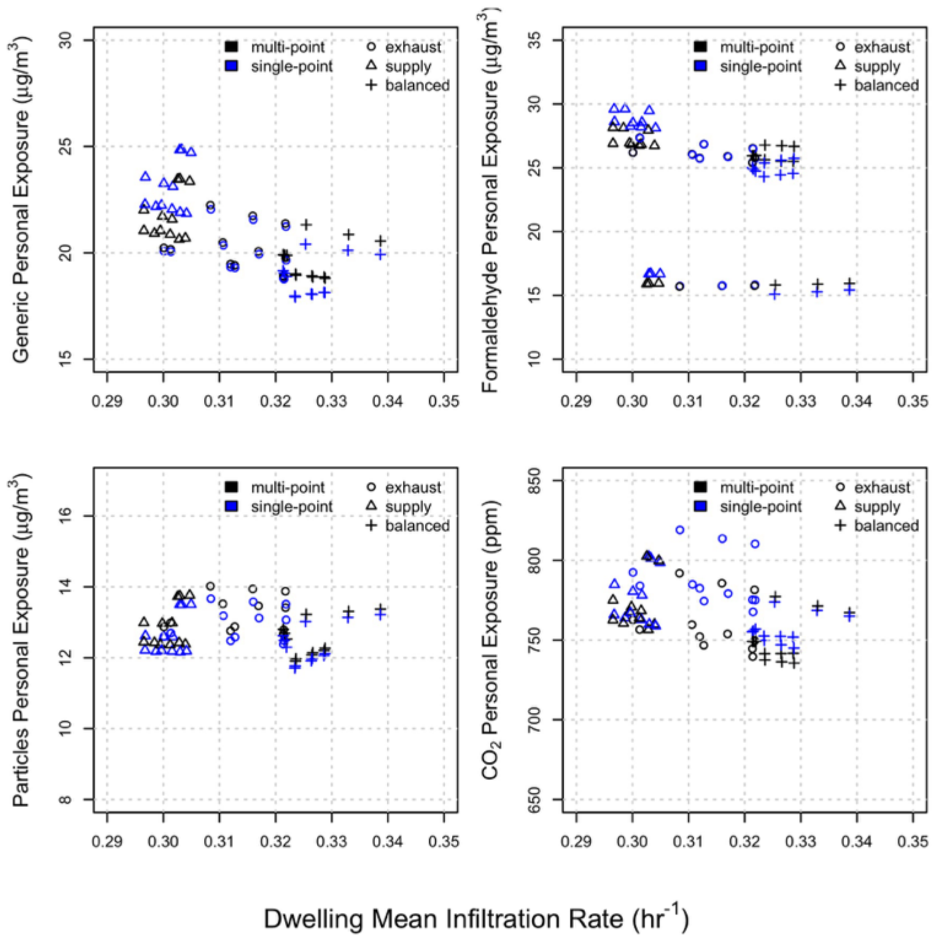

Figure 2 Ventilation Rate and Personal Contaminant Exposures for Each Fan Type and Zoning Type.

CONCLUSIONS

Zonally controlled ventilation systems had HVAC site energy savings (from 0 to 40%) in the 1-story dwelling, while they performed poorly in the apartment dwelling. This was because the apartments were cooling load dominated such that any controls that lowered ventilation rates also reduced ventilation cooling. The energy savings were significantly higher in colder climates. Exhaust fans used the least energy, but they were only effective as zonal systems when large differences in zone concentrations existed (e.g., CO_2 in bedrooms with doors closed at nighttime). Direct contaminant controls were ineffective due to the inability to control formaldehyde below chronic levels. For these tight dwellings (< 3 ACH50), changes in envelope leakage had very little impact on ventilation control performance. The zonal controls often had negative impacts on personal exposure to one or more contaminants of concern, reducing their ability to maintain acceptable indoor air quality while saving energy. Supply ventilation types (including balanced fans) most effectively delivered outside air to the target zones, but they also used much more energy than exhaust systems, due to their recirculation and tempering requirements. The ability of homes to be effectively zoned from an IAQ perspective was also limited (because open interior doors allow considerable interzonal air flow) and movement of occupants between zones. In addition, the increase in contaminants that occupants are exposed to when first entering a previously unoccupied zone means that there is little to be gained by adding extra zones to ventilation controls beyond a simple bedroom/ non-bedroom split.

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